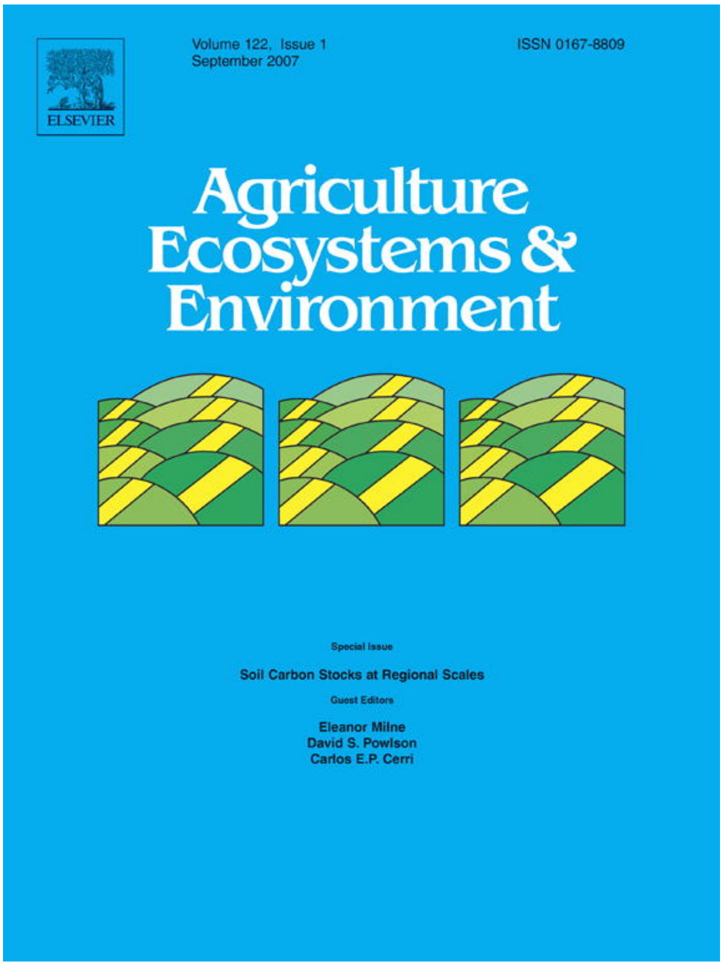

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Soil Carbon Stocks at Regional Scales

Guest Editors

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An increased understanding of soil organic carbon stocks and changes in non-temperate areas: National and global implications

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Abstract

National and sub-national scale estimates of soil organic carbon (SOC) stocks and changes can provide information land degradation risk, C sequestration possibilities and the potential sustainability of proposed land management plans. Under a GEF co-financed project, 'The GEFSOC Modelling System' was used to determine SOC stocks and projected stock change rates for four case study areas; The Brazilian Amazon, The Indo-Gangetic Plains of India, Kenya and Jordan. Each case study represented soil and vegetation types, climates and land management systems that are under represented globally, in terms of an understanding of land use and land management systems and the effects these systems have on SOC stocks. The stocks and stock change rates produced were based on detailed geo-referenced datasets of soils, climate, land use and management information. These datasets are unique as they bring together national and regional scale data on the main variables determining SOC, for four contrasting non-temperate eco-regions. They are also unique, as they include information on land management practices used in subsistence agriculture in tropical and arid areas. Implications of a greater understanding of SOC stocks and stock change rates in non-temperate areas are considered. Relevance to national land use plans are explored for each of the four case studies, in terms of sustainability, land degradation and greenhouse gas mitigation potential. Ways in which such information will aid the case study countries in fulfilling obligations under the United Nations Conventions on Climate Change, Biodiversity and Land Degradation are also considered. The need for more detailed land management data to improve SOC stock estimates in non-temperate areas is discussed.

Keywords: The GEFSOC Modelling System; Soils; Soil organic carbon; Soil organic carbon stock change; Land use; Non-temperate

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1. Introduction

Between June 2002 and July 2005, the Global Environment Facility (GEF) co-financed project (number GFL-2740-02-4381) developed and demonstrated a system for producing spatially explicit estimates of soil organic carbon (SOC) stocks and changes at the national and sub-national scale. Models and methods developed by research groups working in the USA and UK (Paustian et al., 1997, 2002; Falloon et al., 1998, 2002) were used to develop The GEFSOC Modelling System (Easter et al., 2007; Milne et al., 2007). The project produced SOC stocks and projected stock change rates for four case study areas; The Brazilian Amazon, The Indo-Gangetic Plains (IGP) of India, Kenya and Jordan (Table 1). Estimates were made using two simulation modelling methods Century (Parton et al., 1987) and RothC (Coleman and Jenkinson, 1999) and the Intergovernmental Panel on Climate Change (IPCC) Tier I (default) computational method, which are all components of The GEFSOC Modelling System. Stock change estimates were made for the period 2000–2030 under likely land use change scenarios. In this preliminary assessment, climate change was not taken into account and the drivers considered were exclusively land use and land management.

At the beginning of this project and at the present time, studies of SOC stock changes in temperate areas far outnumber studies in non-temperate areas, although the balance is beginning to be redressed (Ardo and Olson, 2003; Grace et al., 2004; Ponce-Hernandez, 2004). The four case studies used in the GEFSOC project therefore represent soil types and climates that are under-represented globally, in terms of an understanding of land use and land management systems and their effects on SOC. They also cover a diverse range of land uses, drivers of land use change and land use change patterns; from the Brazilian Amazon – dominated by recent land use change in the form of deforestation, to the Indian IGP – cultivated for hundreds of years, but in a state of change in terms of cropping intensity and crop diversification. This paper discusses implications of a greater understanding of SOC stocks and stock change rates in non-temperate areas. The stages involved in using the GEFSOC Modelling System to make estimates of SOC stocks and stock changes are given in detail in other papers in this special issue (Milne et al., 2007; Easter et al., 2007), as are detailed accounts of the SOC stocks and stock changes for the four case study areas (Al-Adamat et al., 2007; Bhattacharyya et al., 2007; Cerri et al., 2007; Kamoni et al., 2007). The purpose of this paper is, therefore, not to repeat this information but rather to discuss how the information is relevant to national land use plans and United Nations Environmental Conventions.

Table 1
Soil organic carbon stocks and stock change estimates for the years 2000 and 2030 made using the GEFSOC Modelling System

Area	GEFSOC modelling system outputs SOC stocks Tg C		
	RothC (0–20 cm)	Century (0–20 cm)	IPCC (0–30 cm)
Year 2000			
Amazon Brazil	27,003	32,603	26,951
Jordan	102	66	242
Kenya	1,522	1,415	2,009
IGP, India	–	1,324	1,381
Year 2030			
Amazon Brazil	25,004	30,431	23,391
Jordan	100	57	249
Kenya	1,308	1,311	1,975
IGP, India	–	1,265	1,381
Estimated SOC stock change 2000–2030, Tg C			
Amazon Brazil	−1,999	−2,172	−3,560
Jordan	−2	−9	+7
Kenya	−214	−104	−34
IGP, India	–	−59	0

The SOC stocks and stock change rates produced during The GEFSOC project were based on detailed geo-referenced datasets of soils, climate and land use information. These datasets are, to the authors' knowledge, unique as they bring together national and regional scale data on the main variables determining SOC, for four contrasting non-temperate eco-regions. All of these datasets are in a comparable standardised format and are available via the GEFSOC project Website (http://www.nrel.colostate.edu/projects/gefsoc-uk). Of the types of data collated, land use and land management information proved to be the most difficult to assemble, both for current and historical cases. Most information was gathered from government statistics in paper format and put into electronic format. The importance of land use (both current and historical) to SOC stocks has been highlighted (Pulleman et al., 2000; Parton et al., 2005) and yet there is still a paucity of information on this subject, especially for agricultural systems in developing countries. This paper therefore, also discusses a need for more land use/management information, especially relating to subsistence agriculture in non-temperate areas.

2. Background information on the case study areas

Fig. 1 shows the location of the four case study areas considered in the GEFSOC project.

These particular locations were chosen for a number of reasons:

(1) As can be seen from Fig. 1, the chosen case studies span a wide area geographically, being located in three continents. They therefore represent a range of different soil types and climates. The Brazilian Amazon has a hot humid climate, experiencing precipitation of up to 3000 mm $year^{-1}$ in some places. However, due to the vast area covered by the region (>5,000,000 km^2) local climate varies throughout. Two soil orders (Oxisols and

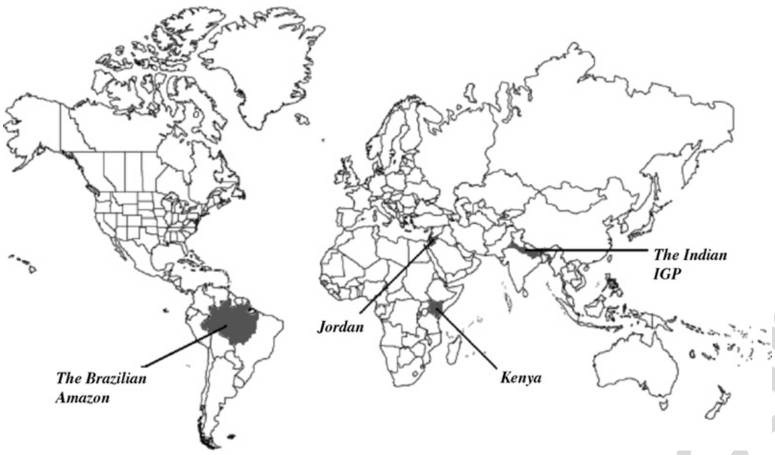

Fig. 1. Location of the GEFSOC project case studies.

Alfisols) dominate, covering ~75% of the area (Cerri et al., 2007). In contrast, Jordan covers a relatively small area (89,206 km^2) and has an extremely arid climate with 80% of the country being classed as desert and receiving precipitation of <200 mm year^{-1} (Al-Adamat et al., 2007). Soils in Jordan include Aridisols, Inceptisols, Entisols and Vertisols. The predominantly flat alluvial plains of the Indian IGP become increasingly humid as you travel from west to east with precipitation ranging from 300 to 1600 mm year^{-1} (Bhattacharyya et al., 2007). Soils are mainly Entisols, Inceptisols and Alfisols across the ~467,000 km^2 covered by the Indian part of the plains. Considering the area covered (582,646 km^2), Kenya encompasses a diverse range of climatic conditions from arid (rainfall 150 mm year^{-1}) to humid (2500 mm year^{-1}) (Kamoni et al., 2007). A wide rang of soil types are also found in the country including Entisols, Alfisols, Oxisols and Ultisols.

(2) A prime consideration in choosing case study areas was the availability of data particularly soils data. Data was needed that could be put into a consistent format. This would allow comparable SOC stock estimates to be produced for the different case studies. Three of the case study countries already had soil and terrain (SOTER) databases. The exception (India) had a detailed soils map from which a SOTER was produced. The existing SOTER databases had gaps in terms of many of the attributes (e.g. bulk density) needed to run RothC and Century. Theses gaps were filled using a consistent method developed by ISRIC (Batjes et al., 2007). This produced complete soils datasets that could be used for modelling purposes. Each case study country also had local climatic datasets available from a variety of sources including national weather service records, meteorological department records and information from previous scientific projects. Each case study was able to put together climatic datasets with the parameters needed to run the models (monthly precipitation and monthly maximum and minimum air temperature). As mentioned in Section 1, land use data was the most difficult to obtain. However, each case study area considered here had access to government reports or statistical records, from which they were able to create historical and current land use datasets.

(3) Another practical consideration was the prior existence of scientific groups working on relevant issues in the case study countries. This was necessary in order to effectively complete the project within 3 years.

(4) The Project's choice of case study areas was also influenced by the GEF's (the projects major funding body's) choice of priority countries.

3. GEFSOC SOC stock estimates: relevance to national land use plans

3.1. The Brazilian Amazon

The Brazilian Amazon is an area dominated by comparatively recent land use change, namely the conversion of tropical forest to pasture or crop land. Approximately, 80% of the area is still under native vegetation but the area also has the highest rate of deforestation in the world. During the late 1980s and 1990s, an estimated 0.7% of the area was lost to deforestation each year (Anderson, 1990). In recent years (2002–2003), this rate has increased dramatically (by ~48%) in four states: Para, Mato Grosso, Rondonia and Acre. In the same year, an estimated 2.375 million ha were deforested throughout the Brazilian Amazon (Simon and Garagorry, 2005). Deforestation in the region is driven by logging and land clearance for cattle ranching and commercial agriculture. The current boom in soybean (*Glycine max*) production in Brazil is an increasingly important cause of deforestation both directly, as land is cleared and planted to soybean and, more importantly, indirectly as conversion of existing grazing land to soybean drives cattle ranchers to clear new areas of forest (Fearnside, 2001).

The GEFSOC project used a land use change scenario for the Brazilian Amazon, for 2000–2030 that was based on deforestation rates over the past 20 years, some 60 years of agricultural census data and FAO predictions of agricultural expansion in the area. This 'business as usual' scenario, assumed a deforestation rate of 20,000 km^2 $year^{-1}$ with deforestation continuing to be most intensive in the southern and eastern sections of the basin. The increasing importance of soybean production as a driver of deforestation was taken into account in the scenario, with an estimated 70% of newly deforested land being cleared for soybean production by 2030 (Cerri et al., 2007).

The total SOC stock estimated by The GEFSOC project for the Brazilian Amazon in the year 2000 was 27,003 and 32,603 Tg according to RothC and Century, respectively, and 26,951 Tg according to the IPCC method (Table 1) (Cerri et al., 2007). The highest stocks were associated with native forest and well managed pasture. Estimated stocks for the year 2030 were 25,004 and 30,431 Tg according to RothC and Century, respectively, and 23,391 according to the IPCC method (Table 1). Between 1990 and 2030, under a scenario of continued land use conversion, Cerri et al. (2007) estimate an overall loss of 4200 Tg C from soils. Most of this would be associated with the loss of native forest although some losses would also result from the degradation of rangeland. Under the same scenario, gains in SOC stocks (from 217 Tg in 1990 to 620 Tg in 2030) are projected as secondary vegetation becomes established on abandoned areas. Slow gains are also projected for well managed pasture during the same period. The system projects gains in SOC stocks associated with soybean production. This can be attributed to soybean usually being grown with a cover crop such as millet (*Pennisetum glaucum* (L.) R.Br.) and the tendency to grow the crop under a no-till system after 2 years or so (Cerri et al., 2007). As soybean is such a new crop in this area, there are no long-term data on the effects of soybean production on SOC in the Brazilian Amazon. Studies are urgently needed, given the rising importance of this cropping system.

In the case of the Brazilian Amazon, SOC stock changes have to be considered in the context of the huge losses (~100–200 tonnes C ha^{-1}) of C from above ground biomass associated with deforestation (Dias-Filho et al., 2001). Therefore, any gains in soil C associated with well managed pasture systems or no-till soybean production are very small when considered in terms of entire system C losses. The most obvious land use policy recommendation is, therefore to halt or at least reduce deforestation. The Brazilian Government is currently trying to shift from a policy favouring land clearing to one where land owners can only clear a percentage of the area they own. However, this and other forest protection policies are difficult to enforce, with deforestation rates continuing to increase. They are also exacerbated by agricultural subsidies that encourage deforestation (Fearnside, 2001).

Land ownership policy and land prices also need to be revised. Currently, forested land is cheaper than cleared land. This makes it more attractive for small scale farmers to buy forested land and clear it rather than settling on already cleared land. Policy makers argue that there is enough cleared land in states such as Mato Grosso to increase agricultural production without further deforestation (La Rovere and Santos Pereira, 2005). However, until the price differential for forested and cleared land is addressed this is unlikely to happen. The problem is exacerbated by the land ownership policy of the Brazilian Government that gives anyone who lives on a patch of land for 5 years the 'usefruct' right to own it (Cerri et al., 2007).

The SOC stock changes estimated by the GEFSOC project show the long-term advantages of good pasture management. Several studies have shown that under good management, pasture can reach or even surpass SOC levels found under native forest (Cerri et al., 1991; Moraes et al., 1995; Neill et al., 1997). Another policy recommendation to increase SOC stocks, should therefore be enforcement of measures to reduce overgrazing such as minimising stocking rates and using appropriate pasture species on the 50% plus of degraded pasture land in the Brazilian Amazon.

3.2. *The Indian Indo-Gangetic Plains*

At the other end of the spectrum to The Brazilian Amazon, is the Indian IGP. The IGP has a long history of cultivation going back hundreds of years with, traditionally, the eastern areas growing rice (*Oryza sativa* L.) and the north western areas growing maize (*Zea mays* L.) with wheat (*Triticum aestivum* L.) having dominated the area since 1965. In the past 40 years, following the green revolution and with the introduction of higher yielding dwarf varieties, the Indian IGP has become dominated by a rice/wheat rotation (Kataki et al., 2001). The main issue in the IGP has, therefore, been one of intensification of agricultural land use and changes in cropping patterns, rather than change from one land use to another. Current land use information for the Indian IGP, gathered for the GEFSOC project shows 50% under a rice/wheat rotation, 45% under some form of double or triple cropping system, 1% under fallow rice, with the remainder under other systems including a small amount of natural forest (Bhattacharyya et al., 2007).

In 2002, The Planning Commission of The Government of India published a document entitled 'India Vision 2020'. This document sets out a plan for India between 2000 and 2020, which aims to meet a number of economic, social and environmental goals. The emphasis of the document is the continuing transformation of an agrarian economy into a more diverse economy. The document also points out that in recent years food production has increased at a greater rate than population growth and that India now produces a surplus of rice and wheat (Gupta, 2002). Vision 2020 therefore advocates diversification of crops produced as this would allow the government to wean farmers off subsidies and meet growing national demand for a wider range of crops (Gupta, 2002). The GEFSOC project used the trends outlined in Vision 2020s BUS scenario, in conjunction with FAO projections, to devise a land use change scenario that predicts an increase in the number of crops grown in a season and a diversification in the types of crops grown. For example, in the north Punjab Plains, recent years (1996–2004) have seen an increase in vegetables being introduced into predominantly rice wheat rotations. The GEFSOC project scenario assumes this trend will continue, with vegetables or oil seed crops being part of almost all rotations in the area by the year 2030 (Bhattacharyya et al., 2007).

For the year 2000, the GEFSOC Modelling System estimates the total SOC stocks for the Indian IGP as ~1324 Tg according to the Century output) and 1381 according to the IPCC method (Table 1) (Bhattacharyya et al., 2007). The RothC outputs for the Indian IGP were unrealistically high and are therefore not shown here. All of the multi crop systems involving rice had C stocks of ~30 Mg ha^{-1}. The Century output showed triple crop systems to have lower stocks than the double crop systems, probably due to lower crop residue returns associated with vegetable production. Of all the cropping systems, the rice fallow system had the highest per ha SOC stocks, however, rice fallow covers ~1% of the total area and therefore contributed little to the overall stock. Similarly, forest and pasture reserves had the highest per ha stocks of any land use but occupy less than 1% of the total area.

Estimated total SOC stocks for the year 2030 were the same as those for 2000 according to the IPCC method (1381 Tg) but slightly less (1265 Tg) according to the Century output (Table 1). According to the modelling output, the land use change scenario for 1990–2030 shows small SOC losses between 1990 and 2000 associated with conversion of pasture and forest to cropland. However, overall there is a gain in SOC during 1990–2000, associated with an increase in productivity. Between 2000 and 2030, this increase is lost and projected stocks fall back to 1990 SOC levels. This is due mainly to an increase in triple cropping systems at the expense of rice/fallow and double cropping systems.

Output from the GEFSOC project has shown that a move to triple cropping systems involving a wider range of crops in the Indian IGP (as advocated by Vision 2020) could lead to a decrease in SOC (Bhattacharyya et al., 2007). However, the levels of SOC in the double cropping rice wheat system are associated with higher productivity and an assumption of higher returns to the soil. Under continued rice/wheat, SOC increases are projected to reach equilibrium by the year 2020 in clay soils and to have already reached equilibrium by 2000 in sandy soils. Several studies have shown declining yields of rice and wheat in the IGP in recent years (Kataki et al., 2001; Pingali and Shah, 2001) and sustainability of the system has been questioned (Duxbury, 2001). Diversification of crops grown in the Indian IGP has the potential to reduce irrigation in the area, especially if less rice is grown. It is estimated that consumption of water by non-agricultural sectors in India will double by 2025, making less water available for irrigation (Hazell and Rosegrant, 2004). Less irrigation could reduce salinisation problems that affect large parts of the Indian IGP (Agrawal et al., 2004). At present, the GEFSOC Modelling System does not account for salinisation and subsequent effects on SOC, however, the system developers are hoping to address this in the future. Diversification of crops grown therefore appears to be a reasonable strategy although this should be done with a mixture of double and triple cropping systems. The GEFSOC Modelling System also showed the SOC benefit of systems involving fallow. A rotation of different systems with some involving fallow could take advantage of this benefit without reducing yields too drastically.

The land use scenario used in the GEFSOC project for the Indian IGP was a ‘most likely’ case. It did not include moves to SOC friendly practices such as no-till. No-till in the larger IGP is increasing, however, adoption is slow due to cultural resistance and problems with weed control (Hobbs and Gupta, 2004). Although perceived as predominantly rice/wheat, The Indian IGP is actually a very complex mix of different cropping systems. More information is needed about these systems in order to improve SOC change estimates.

3.3. Jordan

Jordan is an arid country with most of its land area traditionally being under nomadic pastoralism. However, today the majority of the population live in urban centres such as Amman and rely on the heavily irrigated Jordan Valley. In the last century, land use change in Jordan has been driven by a number of complex factors including immigration from neighbouring countries facing political instability and Jordan’s own high rate of natural population increase (Dutton, 1998). The result has been over grazing leading to degradation of rangeland (~80% of the country can be classed as degraded rangeland), a growth of subsistence agriculture and an increase in intensively irrigated agriculture in the Jordan Valley.

As expected, the GEFSOC project showed SOC stocks in Jordan to be low, reflecting the arid climate. Stocks for the year 2000 were 102 and 66 Tg C according to RothC and Century output from the GEFSOC Modelling System, respectively (Table 1) (Al-Adamat et al., 2007). IPCC estimates were much higher at 242 Tg (Table 1). Despite the difference between the two modelled estimates, stock distribution between land classes was similar, with rangeland accounting for about 70% of the stock, cropland about 20% and other land uses such as forest, managed pasture and olive (*Olea europaea*) groves the remaining 10%. Nationally, appropriate management of rangeland is therefore important as it is the predominant land use in the country and management of cropland is important as it represents a more concentrated SOC stock (16–25 tonnes C ha^{-1}). For the year 2030, estimated national SOC stocks for Jordan were 100 and 57 Tg according to RothC and Century, respectively, and 249 Tg according to the IPCC method (Table 1).

The project used a land use change scenario for 2000–2030, for Jordan based on extrapolation of current trends taken from government statistics and FAO projections of future land use. An increase in urbanisation at the current rate is assumed, accompanied by an increased demand for water. Intensification of irrigation in the Jordan valley is also predicted putting further demand on already scarce water resources. However, the most important land use prediction in the scenario is the continued overgrazing in the Badia region leading to further degradation of good rangeland. This drives SOC stock decline from the year 2000–2030 at a rate of ∼0.5% year^{-1} according to the Century model (Al-Adamat et al., 2007). Some small increases in SOC stocks are predicted in the Jordan Valley between 2015 and 2030. This is due to vegetable production being replaced by banana (*Musa X paradisiaca* L.) and citrus (*Citrus* sp.) production (Al-Adamat et al., 2007). However, this scenario assumes Jordan will still have sufficient water to maintain current irrigation levels in 2030.

Declining SOC stocks in the Jordan Badia region (where the majority of rangeland is located) will have serious consequences, potentially leading to irreversible land degradation and desertification. Measures to reduce overgrazing and allow rangeland regeneration should therefore be a priority for Jordanian policy makers if existing SOC stocks are to be safeguarded. Excessive overgrazing began in the Jordanian Badia during the 1990s. Subsidies led to a massive increase in the number of sheep and goats in the region, having a detrimental effect on traditional nomadic grazing practices. Some national initiatives to address overgrazing problems are in place such as rangeland management agreements with Bedouin and research into drought tolerant species (BRDC, 2004, personal communication). However, the problem is complex involving socioeconomic and cultural as well as environmental factors.

Land degradation in the Badia has a knock-on effect on land use in the rest of the country. The Jordanian Ministry of Agriculture cites rural to urban migration as a key problem in Jordan (MoA, 2003). A growing urban population will have increased water demands, creating more competition for water resources with other sectors such as agriculture. This has implications for the SOC stocks in the heavily irrigated Jordan Valley. Experts from Jordan have argued that the production of many of the crops grown in the Jordan Valley makes no sense in economic terms or in terms of water use (Al-Weshah, 2000). In general, the same products can be imported at a lower price. However, political instability in the wider region has dictated a policy of self sufficiency and unless circumstances change, Jordan is likely to continue growing heavily irrigated crops in the Jordan Valley.

3.4. Kenya

Of the four case studies considered, Kenya has the most complex land use. This is a reflection of the variety of climatic zones in the country that range from humid to very arid. Like Jordan, Kenya is dominated by grazing land with ∼40% of the country being used for grazing. Another 37% is under subsistence agriculture, a proportion that is rising, with the main land use change in the country being the conversion of savannah or grazing land to subsistence agriculture. The remaining 20% is used for commercial agriculture and plantations and a small amount (∼2%) is natural forest (Kamoni et al., 2007). In Kenya, land use change has been and continues to be, influenced by conversion of native ecosystems to agriculture.

GEFSOC national SOC stock estimates for Kenya were ∼1400–1500 Tg for the year 2000 using the two modelling methods (Table 1) (Kamoni et al., 2007). The largest C stocks were associated with grazing land as this occupies the largest area of the country. Native forest had the highest C stocks on a per hectare basis (∼80 Mg C ha^{-1}). Following forest, commercial agriculture and plantations had the highest per area SOC stocks reflecting higher inputs and production. SOC stocks for subsistence agriculture and grazing land, when considered on a per area basis, were a quarter of that found under native forest. Grazing lands tend to occur in the driest areas of the country where agricultural opportunities are limited. Estimates made for Kenya using the IPCC Tier I method within the GEFSOC Modelling System were higher (2009 Tg) than estimates made using the two simulation modelling methods (Table 1). National SOC stock estimates for the year 2030 were almost identical for the two modelling methods at 1308 and 1311 Tg and again higher using the IPCC method at 1975 Tg (Table 1).

The land use change scenario between the year 2000 and 2030 for Kenya assumed continued conversion of natural savannah (in the semi-arid regions of Kenya) to subsistence agriculture. Native forest in existence in the year 2000 was assumed to remain. This was based on an assumption that the Government of Kenya's forest preservation plans would be successful (GoK, 2002). Using this scenario, the GEFSOC Modelling System (Century output) estimated a national decline in SOC stocks of ∼100 Tg over the 30 year period. Small gains occur with some high input agricultural systems such as tea (*Camellia sinensis* L.) production, but these are outweighed by the overall decline.

The findings of the GEFSOC project suggest that in order to maintain SOC stocks in Kenya in the next 30 years, efforts should focus on the sustainable use of existing grazing lands and a reduction in the rate of conversion of savannah and grazing lands to subsistence agriculture. Loss of SOC would lead to an increased risk of soil erosion, a lowering of soil fertility and a lowering of the soils capacity to store water. This last point is especially important as Kenya receives rainfall in two distinct rainy seasons and water storage capacity can therefore prolong the growing season. Kenya has in place environmental legislation aimed at the sustainable use of soil resources. The 'Agricultural Rules' of 1965 prohibit land uses that are likely to lead to soil erosion such as grazing of livestock on sloping land and the 'Agriculture Act' stresses preservation of soil fertility (Angwenyi, 2004). In addition, in recent years environmental legislation in Kenya has been centralised with the formation of the National Environment Management Authority (NEMA). However, as with many countries, enforcement of environmental legislation rather than the legislation itself is the problem.

Initiatives such as The Forest Range Rehabilitation and Environmental Management Strengthening (FORREMS) programme have had success in several areas of the country (MENR, 2004). However, encouraging sustainable use of grazing lands and reducing conversion to subsistence agriculture is made difficult by Kenya's complicated land tenure system. Three land tenure systems are in effect: (1) communal, which recognises traditional land ownership by tribes, (2) public, which covers trust and government owned land and (3) individual, which covers individual freeholds and leaseholds (NEMA, 2003). In recent years, this system has led to a sub-division of land, leading to a multitude of owners and a degradation of resources. The situation is compounded by the fact that only 18% of Kenya is deemed to be high to medium potential agricultural land (Kamoni et al., 2007) and that 57% of Kenyans live below the poverty line (NEMA, 2003).

As mentioned earlier, the GEFSOC project assumed that remaining forests in Kenya would be preserved between 2000 and 2030. Based on this assumption, no SOC losses from the conversion of forest to cropland were included in the estimates. This may have been a generous assumption. The sustainable supply of woodfuel in Kenya was estimated to be 15 million metric tonnes in 2004 whereas demand in the same year was estimated at 35 million metric tonnes (MENR, 2004). Continued growth in demand will therefore lead to a loss of forestland with resultant loss of SOC.

3.5. A comparison of the four case study areas

One of the major reasons for choosing the four case study countries considered in this project was the wide range of environmental conditions they represent. They also represent a range of different land use policies and priorities that are likely to be major drivers of SOC stock change in the future. Some parallels can be drawn, the most obvious of which is the fact that all case study areas show a predicted decline in SOC between 2000 and 2030 under the 'business as usual' scenarios considered here. In both the Brazilian Amazon and Kenya it is likely that land ownership and land tenure issues will play an important role in determining SOC stocks in the future. This is a reflection of the fact that these two case study areas are greatly affected by changes in land use rather than changes in land management. Conversely, SOC stocks in the Indian IGP and Jordan are more likely to be influenced by further intensification of existing land use. The future management of grazing lands is an issue in Jordan, Kenya and the Brazilian Amazon with overgrazing likely to influence future SOC stocks in all three. Policies that promote sustainable use of grazing lands therefore need to be developed in all three areas.

The land use/management scenarios for all case studies areas assume resources (most importantly water) will continue to be available at the current (year 2000) level. This has major implications for the two case study areas with large arid and semi-arid regions, Jordan and Kenya. As pointed out in Section 1, as this work is a preliminary assessment, the scenarios considered do not account for climate change, or the interactions between climate change and land use change. Future work needs to address this issue.

4. SOC stock estimates and United Nations environmental conventions

4.1. The Brazilian Amazon

Preservation and appropriate management of the Brazilian Amazon would allow Brazil to simultaneously meet obligations under the United Nations Framework Convention on Climate Change and The United Nations Convention on Biological Diversity. The Amazon is home to an estimated 40–50% of the earth's species (Meyers, 1981). Unlike industrialised countries, the majority of green house gas (GHG) emissions in Brazil result from land use, land use change and forestry (LULUCF) rather than the energy sector. Some 55% of the country's GHG emissions come from LULUCF and a further 26% from agriculture (MST, 2004). The global importance of these emissions is apparent from the fact that Brazil is the world's 8th largest emitter of greenhouse gases (Kintisch and Buckheit, 2006; Fearnside, 2006).

In 2004, Brazil produced an initial communication to the UNFCCC (MST, 2004). This document includes Brazil's first GHG inventory for the period 1990–1994. The inventory covers GHG emissions and removals by all sectors and includes a section on 'net CO_2 emissions by mineral soils'. The authors used the method suggested by the IPCC (IPCC/OECD/IEA, 1997), which calculates differences in C emissions in one step over a 20-year period. Output from The GEFSOC Modelling System improves on the estimates presented in this inventory in several ways. Firstly, authors of the national inventory used several IPCC default inputs due to a lack of specific information for Brazilian conditions. The GEFSOC project used soils, climate and land use information specific to the Brazilian Amazon. This was particularly relevant in the case of land use data as GEFSOC SOC estimates are the first to use actual land use data for the area. GEFSOC estimates also used substantial information on land use history, including new information not used in the national inventory. The calculation for the first national inventory (Bernoux et al., 2001) was done separately for each Brazilian state and subsequently summarized for all of Brazil. The GEFSOC estimates used data compiled on a county ('municipios') basis. Further details of the approach used to deal with land use history information in the Brazilian GHG inventory are given in Bernoux et al. (2001). This has implications for future stock estimations and any predictions of resultant C emissions. Parton et al. (2005) illustrated the importance of historical land use in determining SOC stocks for different agro-ecosystems in the USA. This importance is even more marked in an area such as the Brazilian Amazon where the main land use change is conversion of native vegetation. SOC takes decades to reach equilibrium after a change from steady state native vegetation (Coleman et al., 1997). With these factors in mind, plans are already being made to include GEFSOC SOC change estimates in Brazil's second national communication to the UNFCCC.

4.2. The Indian Indo-Gangetic Plains

According to India's First National Communication to the UNFCCC (submitted in 2004), in 1994, 61% of India's total GHG emissions resulted from the combustion of fossil fuels and an estimated 29% from agriculture (mainly from cattle and rice production) (MEF, 2004). The report includes emissions from soils under separate headings for agriculture and LULUCF. As shown in Section 3.2, the Indian IGP is overwhelmingly used for agriculture (>99%) therefore emissions from soils as a result of dramatic land use change, for example, conversion of forest or pasture to crop land, will be small in this area of the country. Emissions are more likely to result from changes in agricultural management such as, the type of crop grown or the number of crops grown in a season. The authors of the national communication used the IPCC Tier I method to estimate changes in soil carbon and resultant C emissions. They used national soil C information rather than IPCC default values, but also used a limited number of land use classifications, based on IPCC defaults. Results from the GEFSOC project have shown that such land use classifications are too broad for a study area such as the Indian IGP. Double and triple cropping systems come under the same classification and resultant emissions changes are overlooked. Century output from the GEFSOC Modelling System showed an increase, a decrease and then another increase in SOC stocks from 1990 to 2000 to 2030. Conversely, IPCC Tier I output from the GEFSOC project showed no change over the same period. The IPCC GEFSOC estimates used national soil C information and IPCC default land classifications in the same way as the national inventory. This highlights a limitation of the IPCC Tier I method and shows how the specific land management information used to drive the models in the GEFSOC Modelling System could be used to improve estimates of C emissions from soils in future Indian GHG inventories.

4.3. Jordan

Jordan submitted its first national communication to the UNFCCC in 1997. This included a GHG inventory for the year 1994 (GCEP, 1997). As with Brazil and India, the inventory was obtained using the IPCC Tier I method. Estimated annual emissions are given for the conversion of forest and grassland to other uses (374 Gg CO_2 year^{-1}) and the abandonment of managed lands (832 Gg CO_2 year^{-1}). However, it appears that rangelands that became degraded, without necessarily being completely abandoned were not included in the analysis. Century output from the GEFSOC project estimates annual losses of 500 Gg C year^{-1} between 1990 and 2000 from soils alone, a large proportion of which can be attributed to the degradation of rangelands. This suggests that future GHG inventories would benefit from more country specific information, as highlighted in the Jordanian report to the UNFCCC (GCEP, 1997). At 204 Tg, the IPCC total SOC stocks obtained using the GEFSOC Modellling System were much higher than those given by either of the GEFSOC modelling methods (Al-Adamat et al., 2007). IPCC Tier 1 default reference soil C stock values are based on globally averaged data for 'dry' regions, defined as where potential annual evapotranspiration exceeds precipitation. The default stock values were generally too high for the low productivity grassland systems in the predominately very arid climate found in Jordan, which again highlights the benefit of using country specific soils and land use/ management information.

A second UN convention that is perhaps even more relevant to Jordan is the U.N. Convention to Combat Desertification (UNCCD). The combination of high population growth rates, an influx of refugees, arid climate and limited resources has made Jordan particularly vulnerable to desertification. In the National Report on the Implementation of the UNCCD it is acknowledged that

> 'most of the country is subject to some form of desertification' (GCEP, 2002).

The status of SOC can be indicative of risk of land degradation and desertification (Carter, 2002). The predictive capability of the GEFSOC Modelling System therefore provides a valuable tool in terms of meeting obligations under the UNCCD. The consequences of land use/management practices in different soil type/climate combinations specific to Jordan can be scrutinised in terms of future resultant degradation and desertification.

4.4. Kenya

Kenya is a signatory to both the UNFCCC and the UNCCD. From a global perspective, Kenya's GHG emissions are small. Despite this the government is still obliged to produce GHG inventories, including emissions from soils using the most advanced means possible. The GEFSOC Modelling System has enhanced Kenya's capability considerably. The system provides the country with a Tier III inventory method able to account for the complex range of agro climatic and soil conditions in the country. The GEFSOC project has also brought together information on the varied land use practices in Kenya, however, more information needs to be collated to improve estimates further. Kenya's first national communication to the UNFCCC was made in 2002 (GoK, 2002). The communication points out the importance of being able to produce accurate national GHG inventories in the future, especially in terms of the countries capacity as a C sink. Such information is needed to identify areas for potential CDM projects and future C enhancing land management strategies.

The GEFSOC Modelling System provides spatially explicit estimates of changes in SOC stock under land use scenarios pre-determined by the user. It therefore provides a useful planning tool for countries such as Kenya. The majority of Kenya is either arid or semi-arid and is therefore at risk from desertification. The GEFSOC project has shown how continued conversion of grazing land to subsistence agriculture in these areas will lead to substantial losses of SOC in the next 30 years (Kamoni et al., 2007). These estimates should be used as an indicator of the risk of desertification. This would allow appropriate land management strategies to be devised and obligations under the UNCCD to be met.

5. A need for more land use/management information

The GEFSOC project is the first example of SOC stock change estimates based on country specific soils, climate and land use/management information for the Brazilian Amazon, the Indian IGP, Jordan and Kenya. The GEFSOC Modelling System is driven by the events that occur in land management systems, for example, tillage, sowing, fertilizer applications and grazing events. While changes in climate can also be represented in the system, this application was not the primary focus of the study. The GEFSOC user builds land use files (crop, pasture and forest) and associated management events in a graphical user interface. These are then put together to form time sequences of land use and land management (Easter et al., 2007). During the GEFSOC project 14 new and 6 improved country specific crop and pasture files were created (Table 2). The information for these files came from research papers, agricultural statistics and in country expertise in the four case studies. This enabled the project to model previously unmodelled systems such as olive production in Jordan or subsistence maize/bean (*Phaseolus* sp.) production in Kenya.

These new files are part of the GEFSOC Modelling System and can be used to model SOC change in other tropical and arid areas with similar land use systems. However, they only represent a portion of the land use practices used in the case study areas. For example, in the Indian IGP there are many variations on the rice/wheat system involving oilseeds, pulses, fodders and even sugarcane (*Saccharum officinarum* L.) (Kataki et al., 2001). Additional crops may be grown in place of wheat, or as intercrops or in relay. Choice of third crop and planting time can vary from one year to the next dependent on rainfall and market pressures. In addition, cultural practices such as fertiliser application and treatment of crop residue can also vary regionally. Modelled output from the GEFSOC project has shown how these different systems have varying affects on SOC stock (Bhattacharyya et al., 2007). Therefore, even in a seemingly straightforward single land use system such as the Indian IGP, where more than 90% of the area is under commercial agriculture involving rice production, more information on cropping practices is needed to improve SOC stock change estimates.

Table 2
Century model crop and tree parameters introduced or improved upon as part of the GEFSOC project

Crop or tree	Status	Country/region
Native tropical forest	Improved	IGP
Wetland rice (*Oryza sativa* L.)	Improved	IGP
Winter wheat (*Triticum aestivum* L.)	Improved	IGP
Leafy vegetables	New	IGP
Fruiting vegetables	New	IGP
Olives (*Olea europaea*)	New	Jordan
Citrus (*Citrus* sp.)	New	Jordan
Desert rangeland	Improved	Jordan
Fruiting vegetables	New	Jordan
Well-managed rangeland	New	Jordan
Degraded rangeland	New	Jordan
Abandoned land/regenerating forest	New	Brazilian Amazon
Native tropical forest	Improved	Brazilian Amazon
Well-managed pasture	New	Brazilian Amazon
Degraded pasture	New	Brazilian Amazon
Maize (*Zea mays* L.) for subsistence farming	New	Kenya
Beans (*Phaseolus* sp.) for subsistence farming	New	Kenya
Sorghum for subsistence farming	New	Kenya
Coffee (*Coffea Arabica* L.)	Improved	Kenya
Tea (*Camellia sinensis* L.)	New	Kenya

For a country such as Kenya there is an even greater need for more land use information, as most of the country is under subsistence agriculture (37%) or traditional pastoral systems (Kamoni et al., 2007). In general, subsistence agricultural systems are less well documented than commercial ones. In reality much 'subsistence agriculture' in Kenya probably includes some crops grown for cash. The GEFSOC project considered the whole of Kenya and therefore used national agricultural statistics and available information on cropping practices from The National Agricultural Research Laboratory (NARL). A consolidation of information on subsistence agriculture in different geographic areas of Kenya from existing sources (e.g. Tropical Biology and Fertility Programme [TSBF], International Centre for Research on Agroforestry [ICRAF], University of Nairobi, Kenyan Agricultural Research Institute [KARI]) and collation of new information would enhance SOC estimates considerably. This would also help to further identify land use practices associated with SOC depletion and declining soil fertility. Conversely, it may also help to identify practices that can help maintain or improve soil quality. Decreasing soil organic matter has been highlighted as a reason for recent decline in crop production in Kenya (Gicheru et al., 2003).

Land use in the Brazilian Amazon is in a state of flux. Low input small-scale agriculture and large scale cattle ranching is rapidly being replaced by high input and highly mechanised agriculture, especially soybean production. Between 1996 and 1999, the area under soybean production in Rondonia increased from 1800 to 14,000 ha (Fearnside, 2001). Methods of soybean production in the Brazilian Amazon are still in evolution and difficult to track. For example, there is a rapid increase in the use of genetically modified herbicide resistant soybean being grown in the area despite the fact that Brazilian law prohibits the sale of transgenic crops in the Amazon (Monsanto, 2004). This is accompanied by changes in cultural practices such as an increase in herbicide use. Datasets on the long-term implications for soil sustainability are not available although soybean production on similar soils in parts of Bolivia, instigated in the 1970s, led to severe land degradation (Fearnside, 2001). Therefore, the urgency of documenting and analysing the SOC consequences of land use systems, especially agricultural systems, in the Brazilian Amazon cannot be overemphasised.

6. Conclusions

The GEFSOC project estimated SOC stocks and stocks changes for four case study areas in non-temperate regions. The case studies cover a range of soil types, climates and land uses and face a variety of different land use change challenges. Despite this, SOC losses between 2000 and 2030 were estimated for all four case studies under 'likely' land use scenarios. The Brazilian Amazon is dominated by recent land use change, namely deforestation. The GEFSOC project estimated that continued deforestation would lead to SOC losses of 4200 Tg between 1990 and 2030. This is in addition to the huge C losses that will be lost from above ground biomass under the same scenario. The Indian IGP is an area of well established land use, with SOC levels being more stable. However, future SOC losses were estimated in the region due to a potential decline in rice/wheat productivity and a diversification in the crops grown in the area. Jordan and Kenya are both countries with substantial areas of grazing land. Both show estimated net losses of SOC by 2030 if current trends in land use continue. In Jordan, losses will be due mainly to degradation of existing rangelands, in Kenya loss will be due to a continued conversion of savannah to subsistence agriculture. In a related study, estimates of changes in soil and vegetation carbon due to future predicted climate change were also made using the RothC and HadCM3LC models at a much coarser scale than the GEFSOC Modelling System estimates (Falloon et al., 2007). This indicated that soil and vegetation carbon storage is likely to respond differently to climate change in the four case study countries—large reductions in carbon storage were predicted for Brazil, whilst carbon storage could increase in Kenya and smaller changes were likely in India and Jordan. These changes are in addition to the land use change related GEFSOC estimates. Since future climate change could also affect future land use and management options, a next important step will be to more explicitly include climate change impacts in our assessments.

The GEFSOC Modelling System provides a tool for non-Annexe 1 and Annexe 1 countries to report losses of C from soils to the UNFCCC, using a method that accounts for ongoing dynamic soil processes resulting from past land use change. The SOC stock changes produced under the project for Amazon Brazil, The Indian Indo-Gangetic Plains, Jordan and Kenya are the first examples of estimates made using a Tier III inventory method for these areas. The GEFSOC project used these four areas as case studies for the development of the system. Estimates made for these and other non-temperate areas would benefit greatly from more country specific land use information, especially for subsistence agriculture—further developments to the GEFSOC Modelling System should also include availability of resources (e.g. irrigation water) and other socioeconomic factors, and the impacts of salinisation on different systems.

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